Review of Carbon TerraVault (CTV) Responses to EPA's Questions about the AoR Delineation Modeling Approach for the A1-A2 Class VI Project

In January 2022, EPA provided questions (*blue, italic text*) to CTV about the AoR modeling and modeling-relevant site characterization information in the permit application narrative and in the PISC and Site Closure Plan (Attachment E) submitted with CTV's Class VI permit application (dated August 30, 2021) for the proposed Carbon TerraVault (CTV)-Elk Hills Class VI geologic sequestration (GS) project. CTV provided an updated Area of Review and Corrective Action Plan and PISC and Site Closure Plan to EPA on March 31, 2022. EPA's evaluation of how the updated plans address its questions is presented in red below. Requests for revisions and additional information are presented in ***red, bold, and italic*** below. Previous responses that require no further information are not included in this enclosure.

It is assumed, that planned pre-operational testing will confirm the site characterization information. Please note that modifications to the model parameters may be needed if this testing yields results that are significantly different than the model inputs.

Evaluation of the Geomodel

Geomechanical properties

The geomechanical properties of the Monterey Formation A1-A2 reservoir and Reef Ridge Shale confining zone were derived from compressional sonic data and MICP measurements in 18 wells. Borehole breakout data from the EHOF and literature reviews also aided in characterizing fracture behavior. A corresponding geomechanical model was generated to assess the failure pressures for the reservoir and confining zone. CTV included relevant discussion concerning geomechanical modeling and properties in the permit application narrative; please also see the geologic site characterization report for discussion.

A summary of fracture pressure data for the Monterey Formation A1-A2 reservoir is provided in Table 6 of the AoR CA, which is replicated below. The applicant states that injection pressure will be below 90% of the Monterey Formation A1-A2 fracture gradient at the shallowest point of the Reef Ridge Shale base in the AoR (8,403 ft as seen in Table 7 of the AoR CA, replicated below). The planned maximum subsurface wellbore injection pressure for the project is 4,500 PSI.

Table 6: Summary of the fracture pressure data for the Monterey Formation A1-A2 reservoir.

Interval	Fracture Gradient PSI/foot	Fracture Pressure (PSI) at base of Reef Ridge Shale (8,403 feet)
Monterey Formation A1-A2	0.97	8,150

Table 7. Injection pressure details.

Injection Pressure Details	Injection Well 1 357-7R	Injection Well 2 355-7R
Fracture gradient (psi/ft)	0.97	0.97
Maximum injection pressure (90% of fracture pressure) (psi)	7,335	7,335
Elevation corresponding to maximum injection pressure (ft MSL)	8,403	8,403
Elevation at the top of the perforated interval (ft MSL)	8,485	8,462
Calculated maximum injection pressure at the top of the perforated interval (psi)	7,407	7,387
Planned maximum injection pressure / gradient (top of perforations)	4,500 / 0.53	4,500 / 0.53

Questions/Requests for the Applicant:

- *What data from which tests were used to establish the fracture pressure listed in Table 6 of the AoR CA? Additionally, please discuss how testing during the pre-operational phase will further establish the fracture pressure of the injection zone. If Step Rate Testing (SRT) will be used to determine fracture pressure, please describe the testing procedure, including the fluid to be used and how it is representative of the CO_2 injectate. CTV specifies that fracture gradient data in Table 6 (formerly Table 7) was obtained from well 327-7R-RD; however, the details of the tests conducted are not given. CTV added that they will be conducting a step rate test as per their pre-operational testing plan. The response is acceptable, pending receipt of an updated version of CTV's pre-operational testing plan that includes a SRT (which EPA requested as part of the initial geologic review).*

Objectives for Pre-Operational Testing:

- *Confirm the fracture pressure of the injection and confining zones, i.e., by performing an SRT in each zone.*

Evaluation of the Computational Model Design

The applicant's discussion of computational model design includes but is not limited to subsurface phase properties and behavior, CO_2 plume size and extent, boundary and initial conditions, timeframe and time steps, operational information, model calibration and sensitivity analysis, and injection zone storage capacity. EPA considers the applicant's evaluation of the computational model design and

associated components to be appropriate and relatively complete, however there are some outstanding questions that need to be addressed in order to consider the material in this section sufficient.

Boundary conditions

No-flow boundary conditions were established for the Monterey Formation A1-A2 reservoir in the computational modeling. The overlying confining unit, the Reef Ridge Shale, is continuous through the area, has a low permeability (less than 0.01 mD), and has confined oil and gas operations (that include injection) since discovery of the field. Well performance data from the Monterey Formation A1-A2 oil and gas reservoir, shown in Figure 9 of AoR CA, indicates no connection to an aquifer. Historical production shows minimal water production, supporting the lack of aquifer connectivity. Gas injection and subsequent gas blow-down supports lateral and vertical confinement by demonstrating that gas did not migrate out of the reservoir. Finally, reservoir pressure is approximately 230 psi and has not shown an increase due to aquifer influx.

Questions/Requests for the Applicant:

- *Please provide historical pressure data for the Monterey Formation A1-A2 reservoir demonstrating pressure isolation. CTV did not provide any information to address this question.*

Follow-up Questions/Requests for the Applicant:

- ***Please explain the basis for assuming isolation of the Monterey Formation A1-A2 reservoir in the model and provide data to justify the claim.***

Time Steps and Model Timeframe

The computational modeling results for CO_2 plume development at 4 different time-steps are shown in plan view (Figure 10) and cross-sectional view (Figure 11). The time-steps are Year 2 injection, Year 4 injection, Year 50 post injection, and year 100 post injection. The model simulation appears to have occurred over a 115-year timeframe (i.e., the 15-year injection phase plus 100 years post-injection), but this is not clear. For all layers within the model and at all time-steps, the CO_2 plume remains within the 2.1 square mile AoR. Within the first 2 years of injection, the CO_2 plume is largely defined. After 2 years, the CO_2 concentration within the plume increases until the 50 years post injection time-step. The CO_2 concentration is largely unchanged between the 50-year and 100-year post injection time-steps.

CO_2 injected into the Monterey Formation A1-A2 reservoir will be soluble in both water and oil. Due to the low remaining oil and water saturations in the reservoir, the injected CO_2 that will be dissolved in oil and water is predicted to be 0.5% and 1.3%, respectively. The remaining 98% of the injectate will be stored in the reservoir as supercritical CO_2. Figure 12 of the AoR CA demonstrates the cumulative storage for each of these mechanisms (oil, water, supercritical CO_2).

Questions/Requests for the Applicant:

- *Based on Figure 12, there is no additional CO_2 to be stored after year 5 of injection; however, the permit application narrative indicates injection will occur for 15 years. Please clarify this difference. CTV states that 5 years of injection represents the Base Case simulation, and 15 years represents a sensitivity case with a lower injection rate (see Table 7). Typically, the base case represents the anticipated operating conditions; however it is EPA's understanding that CTV plans to inject for 15 years.*

Follow-up Questions/Requests for the Applicant:

- ***Please confirm the injection phase duration and clarify which modeling scenario duration (i.e., 5 years or 15 years) reflects CTV's planned injection operations.***

Initial Conditions and Operational Information

Initial model conditions at the beginning of CO_2 injection have been established and verified over time during oil and gas production from the Monterey Formation A1-A2 reservoir. Initial conditions for the model are given in Table 4, which is replicated below. Operational information is presented in Table 5.

Table 4. Initial conditions.

Parameter	Value or Range	Units	Corresponding Elevation (ft MSL)	Data Source
Temperature	240	Fahrenheit	8,300	Fluid Analysis
Formation pressure	200-300	Pounds per square inch	8,300	Pressure Test
Fluid density	61	Pounds per cubic foot	8,300	Water analysis
Salinity	25,000	Parts per million	8,300	Water analysis

Table 5. Operating details.

Operating Information	Injection Well 1 357-7R	Injection Well 2 355-7R
Location (global coordinates) X Y	 35.32802963 -119.5449982	 35.33139038 -119.5441437
Model coordinates (ft) X Y	 6,100,956.63 2,308,944.30	 6,101,103 2,310,474
No. of perforated intervals	7	4
Perforated interval (ft MSL) Z top Z bottom	 7,728 8,010	 7,774 7,949
Wellbore diameter (in.)	7	7
Planned injection period Start End	 02/01/2024 04/01/2039	 02/01/2024 04/01/2039
Injection duration (years)	15	15
Injection rate (t/day)*	648 – 1,917	648 – 1,917

Questions/Requests for the Applicant:

- *The initial conditions in Table 4 were established at a depth of 8,300 ft MSL. The perforation intervals for Injection Wells 357-7R and 355-7R specified in Table 5 are above 8,300 ft MSL. Please explain how the initial conditions at a depth of 8,300 ft MSL would be representative of the perforation intervals in Injection Wells 357-7R and 355-7R. No explanation was provided.*

- *Please add the reference elevation to Table 4. Table 4 has not been changed. Since the perforated interval on Table 5 was changed to ft TVD, the units between Tables 4 and 5 no longer match.*

Follow-up Questions/Requests for the Applicant:

- ***Please update Table 4 as requested and to match Table 5, and explain how the initial conditions at a depth of 8,300 ft MSL would be representative of the perforation intervals in Injection Wells 357-7R and 355-7R.***
- ***Please update Table 4 or 5 as needed so that the perforation depths are consistent.***

Potential Pathways for Fluid Movement

Faults

CTV included relevant discussion concerning fault stability in the permit application narrative; please also see the geologic site characterization report for discussion.

Wells in the AoR

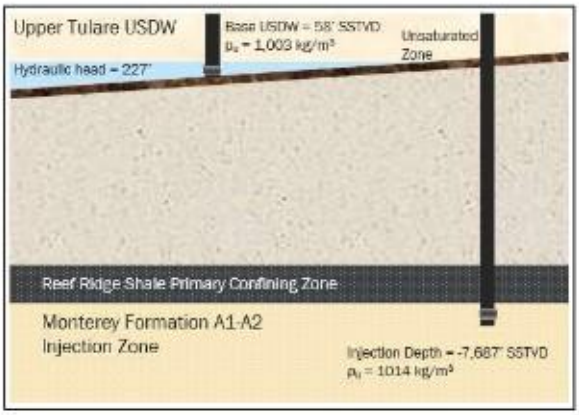
The AoR CA says that complete documentation of the 152 wells in the AoR (tabulated in Table 8 of the AoR CA) that penetrate the Reef Ridge Shale confining zone is given in Appendix 1, and Figure 15 of the AoR CA shows a map view of the 152 wells that penetrate the Reef Ridge Shale confining layer and Monterey Formation A1-A2 reservoir. However, it is unclear how many of the 152 wells penetrate the entire Reef Ridge Shale or are completed in the Reef Ridge Shale, and if they are accounted for in the computational model. Additional discussion regarding wells in the AoR is presented under "Corrective Action on Wells in the AoR," below.

Calculation of critical pressure

CTV submitted their critical pressure calculation to the GSDT in a file titled "Critical—Pressure—Calculation.PDF." Using the inputs from Figure 4 and equation listed on pg. 3 of the Critical—Pressure—Calculation PDF, the critical pressure was calculated to be 3,400 psi. The final pressure of the Monterey Formation A1-A2 reservoir will be at or below the initial reservoir pressure of 4,000 psi, ensuring that post-injection conditions replicate those of initial conditions to the extent possible. Therefore, the AoR is based on the extent of the modeled CO_2 plume.

$$\frac{P_{i,f}}{\rho_i g} + z_i = \frac{P_u}{\rho_u g} + z_u$$

Figure 4: Schematic section of the storage site with inputs to critical pressure calculation. Values for the USDW are based on the 326-7R well. The injection depth is based on the 357-7R injector. Using data from wells 357-7R injector and 326-7R the critical pressure is 3,400 PSI.



Questions/Requests for the Applicant:

- *If any of the 152 wells in the AoR penetrate the entire Reef Ridge Shale, please explain how they are accounted for in the geomodel. No information was provided to address this question within the context of the geomodel.*

Follow-up Questions/Requests for the Applicant:

- ***Please explain, in the context of the geomodel development, how any wells that penetrate the confining zone (and are potential conduits for fluid movement) are accounted for in the geomodel, or why it is appropriate to not include any of the wells that penetrate the confining zone in the AoR within the geomodel.***

Representation of Fluid Properties

Because a baseline injectate analysis has not yet been performed, limited information about the CO_2 stream is available and relevant CO_2 injectate fluid properties for the numerical modeling are not included in the AoR CA. The applicant did not submit an operating plan for the proposed wells with this information. Additionally, the applicant did not include reactive transport modeling as part of the overall modeling effort. It appears this might be due to the low water saturation (~15%) and dominant quartz/feldspar mineralogic framework of the reservoir, as noted in the permit application narrative. However, an explanation regarding the lack of reactive transport modeling is needed.

Questions/Requests for the Applicant:

- *Please update the AoR CA to include fluid properties for the CO_2 injectate used in the computational modeling, including but not limited to viscosity, density, salinity, and fluid compressibility. CTV did not provide this information.*

Follow-up Questions/Requests for the Applicant:

- ***Please describe the model assumptions related to the injectate properties as requested above.***

Objectives for Pre-Operational Testing:

- *Confirm that the properties of the CO_2 stream based on pre-operational injectate sampling are consistent with the model inputs.*

Model Calibration and Sensitivity Analyses

CTV used information derived from extensive past injection operations to inform a sensitivity analysis. The CO_2 plume model results were compared with the area of the reservoir that has been depleted by oil and gas operations.

As a computational model sensitivity, CTV maintained the injection rate for 9 years, with an increase in the final post-injection pressure and total CO_2 injected. The left panel in Figure 13 of the AoR CA represents this scenario, and the panel on the right demonstrates CO_2 plume development at a post injection reservoir pressure equivalent to the initial reservoir pressure. At a final reservoir pressure of 5,750 psi, which is greater than the initial reservoir pressure of 4,000 psi, the reservoir can store 193 BCF of CO_2, which is an increase of 61 BCF relative to initial reservoir pressure storage capacity. Both scenarios demonstrating the difference in CO_2 plume development are depicted in Figure 13 at 100 years post injection. The CO_2 plume remains within the AoR in both scenarios, with CO_2 concentrations increasing in the northwestern portion of the AoR. The applicant concludes that this scenario demonstrates that the AoR is consistent with a larger volume of injected CO_2 and the potential impact to the Upper Tulare USDW is conservative. Monitoring wells will be used for CO_2 plume and pressure front tracking, via fluid sampling and pressure and temperature monitoring. Reservoir pressures based on monitoring data and injection volumes will be integrated in order to complete material balance equations to verify pore volumes and AoR edges. Additionally, the CO_2 plume and water contact will be calculated from the monitoring well pressure, CO_2 saturation, and column height. If the reservoir pressure associated with injected volumes does not follow the anticipated trend from computational modeling, CTV will reevaluate the AoR. (Additional evaluation of the proposed plume and pressure front tracking will be presented in the Testing and Monitoring report.)

Questions/Requests for the Applicant:

- *Please discuss the genesis and evolution of minor CO_2 concentrations pictured in Figure 13 in the central to eastern portions of the AoR. CTV does not discuss this.*
- *Please provide a version of Figure 13 corresponding to the end of the injection period and/or the time at which the plume and pressure front are expected to be at their maximum extent. CTV has not provided an alternate version of Figure 14 (formerly Figure 13).*

Follow-up Questions/Requests for the Applicant:

- ***Please discuss the genesis and evolution of minor CO_2 concentrations depicted in Figure 13 in the central to eastern portions of the AoR.***
- ***Please provide a version of Figure 14 corresponding to the end of the injection period and/or the time at which the plume and pressure front are expected to be at their maximum extent as requested.***

Injection Zone Storage Capacity

As stated in the "Model Calibration and Sensitivity Analyses" section above, the storage capacity of the injection zone appears to be 132 BCF of CO_2 at initial reservoir pressure conditions of 4,000 psi (193 BCF minus 61 BCF as mentioned in the discussion of Model Calibration and Validation of the AoR CA, pg.15). The injection zone does have the potential to store an increased volume of CO_2 at higher pressures while the CO_2 remains within the defined AoR.

Questions/Requests for the Applicant:

- *The modeled injection zone storage capacity is not explicitly stated in the AoR CA. Please confirm if the volume of 132 BCF is correct. If it is not correct, please provide the correct volume. CTV did not revise the AoR CA (or the geologic narrative) to provide the requested information.*

Follow-up Questions/Requests for the Applicant:

- ***Please provide the information requested above about the storage capacity of the injection zone.***

Presentation of Model Results

Map and cross-sectional views of the simulated plume and pressure front were provided in the AoR CA. The maps show the position of the plume and pressure front after 2 years and 4 years of injection, and 50 years and 100 years post-injection. Figures 10 and 11 show the applicant's proposed AoR as delineated by the simulated CO_2 plume.

The differences in the predicted position of the plume and pressure front between the injection and post-injection time-steps were minor, suggesting that the plume movement may remain stable after injection ceases. Updated modeling will be necessary when pre-operational site data becomes available.

Corrective Action on Wells in the AoR

The AoR CA says that documentation of the 152 wells in the AoR that penetrate the Reef Ridge Shale confining zone is provided in Appendix 1. However, no tabulation of these wells is provided. There is an Excel file (AoR—Well--List) containing the name, surface location, and status of 152 wells, but it does not contain information on drill date, type, and depth to Reef Ridge Shale confining zone that is required at 40 CFR 146.84 (c)(2). Table 8 of the AoR CA indicates that 40 of the 152 wells are plugged (which corresponds to information in the Excel file). Figure 15 of the AoR CA shows a map view of the 152 wells that penetrate the Reef Ridge Shale confining layer and Monterey Formation A1-A2 Sands. These wells were reviewed for corrective action.

All 152 wells in the AoR penetrate the confining zone. This determination was made by reviewing open hole logs and deviation surveys of each well. The AoR CA plan says that well condition, mechanical

integrity and data completeness is routinely reviewed with CalGEM. The wells located within the AoR were last reviewed in Q1 of 2021.

The AoR CA also states (pg. 18) that 14 wells (shown in Table 9) will be plugged before commencement of CO_2 injection. These are abandoned wells that penetrate and are currently perforated in the Monterey Formation A1-A2 Sands or the Etchegoin Formation. It is unclear based on the text if these are the only wells that penetrate entirely through the Reef Ridge Shale, however.

The AoR CA plan says that the corrective action assessment for each well in Appendix 1 included the generation of wellbore/casing diagrams, determination of cement tops for each casing string, review of open perforations and cement plug depths. However, Appendix 1 has not been provided.

Protection of the USDW was determined by assessing all wells within the AoR that penetrate the Reef Ridge Shale. Wells were determined to not need corrective action if they had: surface or intermediate casing over the USDW; were cemented over the USDW; had cement in the intermediate casing-surface casing annulus, above the surface casing shoe; and there was cement in the production casing annulus, above the Reef Ridge Shale. The application states that all wells within the AoR meet these criteria.

Questions/Requests for the Applicant:

- *Please provide the plugging and abandonment (P&A) procedure for the 14 wells identified in Table 9 of the AoR CA to demonstrate that plugging will ensure isolation of the Monterey Formation A1-A2 Sands. CTV provided the P&A procedures in Appendix 2 for 31 of the 33 wells to be abandoned, and notes that the remaining 2 wells are being assessed and plugging procedures for them will be provided during pre-operational testing. The response is acceptable at this point; however, CTV should provide plugging procedures for the remaining two wells when they are available.*

AoR Reevaluation Schedule

CTV described the procedures and timing for AoR reevaluations to be performed during the injection and post-injection phases, and the information that will be considered in the reevaluations. At this point in the permit application review, the five-year default reevaluation schedule in the Class VI Rule appears to be appropriate.

Triggers for AoR Reevaluations Prior to the Next Scheduled Reevaluation

An unscheduled reevaluation of the AoR will take place if any of the following scenarios occur:

1) Change in operations such as an increase in injection rates, or injection pressure.
2) Differences between the computational model for CO_2 plume development and observed CO_2 plume development, including unexpected changes in fluid content or pressure outside of the Monterey Formation A1-A2 reservoir that are not related to well integrity, or reservoir pressure that does not behave as predicted with increased injection volumes.
3) Seismic events occur that indicate the presence of faults near/intersecting the confining zone; events that are larger than a 3.5 magnitude and that could be associated with CO_2 injection.

CTV will discuss any such event with the UIC Program Director to determine if an AoR reevaluation is necessary. If an unscheduled reevaluation is triggered, the AoR reevaluation procedures described in the AoR CA plan will be initiated.

Questions/Requests for the Applicant:

- *Please describe the specific injection rate and injection pressure increase CTV referenced that would necessitate an AoR reevaluation, and how such an increase would not involve an exceedance of permit limits. CTV specified that changes in pressure or injection rates outside of three standard deviations from the average will trigger an unscheduled AoR evaluation. However, it is likely that injection pressures as high as three standard deviations above the permit limit would constitute a violation.*
- *Please clarify the degree of change in reservoir pressure (e.g., outside three standard deviations from the average) that would be needed to necessitate an AoR reevaluation. CTV did not specify this degree of change relative to the modeled predictions.*
- *Please clarify the timing for conducting an AoR reevaluation (i.e., within 6 months) if any of the triggering events occur. CTV states that, within six months of a triggering event, CTV will discuss with the UIC Program Director whether an AoR reevaluation is required. EPA recommends that such discussions commence sooner than six months after CTV becomes aware of them, and that the AoR reevaluation be completed within six months.*

Follow-up Questions/Requests for the Applicant:

- ***Please edit the first trigger to not reference an increase in injection pressure as high as 3 standard deviations or explain how such an increase would not be a violation of the injection pressure limit in the permit.***
- ***Please describe, in the second trigger, what degree of reservoir pressure increase relative to modeled predictions would trigger a reevaluation (or if <u>any</u> increase would trigger one).***
- ***Please revise the text at the bottom of page 23 to read, "CTV will discuss any such events with the UIC Program Director as soon as possible to determine if an AoR re-evaluation is required. If an unscheduled re-evaluation is triggered, CTV will perform the steps described at the beginning of this section of the Plan within six months of the triggering event."***

Post-Injection Site Care Plan

Certain elements of the applicant's Post-Injection Site Care (PISC) and Site Closure Plan (Attachment E) are based on the modeling effort and the results and are evaluated below. See also the Testing and Monitoring report (for an evaluation of CTV's post-injection monitoring plan).

As required in 40 CFR 146.93(a)(2)(i) and (ii), the applicant presented the pre- and post-injection pressure differentials and associated maps in the AoR CA. Figure 3 of Attachment E shows the predicted maximum extent of the CO_2 plume and pressure front at site closure.

Figures 4 and 5 of Attachment E show the injection and monitoring wells, and the predicted extent of the CO_2 plume in plan view and cross-sectional view, respectively.

Questions/Requests for the Applicant:

- *Figure 1 in Attachment E shows the reservoir pressure stabilizing at the same time as injection cessation. Please clarify if reservoir pressure will stabilize at this point, or if pressure will stabilize a year after injection cessation as noted in Attachment E, "Pre- and Post-Injection Pressure Differential [40 CFR 146.93(a)(2)(i)]." CTV states in its responses above that the plume will stabilize 1 year post-injection; however, it appears that the line in the figure that represents reservoir pressure becomes horizontal very soon after injection ceases.*
- *Please update Figure 1 to reflect the planned 15-year injection period. The figure was not revised. (As described elsewhere, the duration of CTV's planned injection phase remains unclear.)*

Follow-up Questions/Requests for the Applicant:

- ***Please confirm that injection pressures will stabilize within less than one year post-injection, and describe the basis for this, and update the curve in Figure 1 as needed.***
- ***Please update Figure 1 to reflect the planned 15-year injection period to be consistent with the narrative.***